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Using Simulation to Evaluate the Safety of Proposed ATC Operations and Procedures

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16. Abstract

This report considers some of the problems that arise when simulation is used to evaluate capacity-enhancing system changes that may also affect safety. It proposes a safety standard that is not based on meeting a predetermined or absolute criterion, but on the ability to demonstrate that the proposed system is as safe as the present one assuming the present system is considered safe. Conversely, a change intended to increase safety would be required to show significantly safer operations vis-a-vis the present standard and, perhaps, no loss of capacity.

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EXECUTIVE SUMMARY

This report addresses some of the issues that arise when simulation is used to evaluate capacity-enhancing air traffic control (ATC) system changes that may also affect safety. It examines the limitations of different approaches to the measurement and prediction of safety.

A safety standard is proposed that is not based on meeting a predetermined or absolute criterion, but on the ability to demonstrate that the modified system is as safe as the present one -- assuming the present system is considered safe.

If the intent of change is to improve system safety rather than to increase capacity, this approach would require showing significantly safer operations vis-a-vis the present standard and, perhaps, no loss of capacity.

This approach is based on the concept of ATC simulation as a controlled experiment. It provides a defense against having results contaminated by a lack of complete realism in the simulation, by a paucity of hard data on the occurrence of system errors, and by the difficulty of setting a standard for an acceptable probability of serious events.

INTRODUCTION

BACKGROUND.

SAFETY CRITERIA FOR SYSTEM CHANGE. Questions of system safety and the interpretation of data are complex. The writer believes the absolute requirement for modifying standard procedures is the demonstration of undiminished safety. This can be done in a number of ways:

1. Demonstrate, through the collection and analysis of operational data, that present standards are unnecessarily restrictive.

2. Conduct flight tests proving the feasibility and safety of proposed changes.

3. Conduct operations research, math modeling, or fast time simulation and examine the impact of proposed changes on a variety of operational parameters and contingencies.

4. Conduct real time air traffic control (ATC) simulation studies of the present and the changed system, introduce errors and failures, and compare the results.

These approaches are neither independent nor mutually exclusive. Reliable field data are essential for successful modeling and for simulation. Real time ATC and flight simulation and flight testing are needed to generate estimates of the operational parameters used for modeling and fast time simulation. Modeling provides a framework for collecting and analyzing field data.

The desire to provide absolute certainty in the outcome of an extremely rare event may reduce system capacity below acceptable limits, or worse, produce new and higher risks in other areas now considered safe.

Ultimately, it falls to experienced system users (controllers, pilots, operations personnel, etc.) to weigh the sometimes conflicting evidence from these sources and make the decision, based on their understanding of (1) day in, day out operations, (2) the knowledge and skills of the controllers, and (3) kinds of contingencies the system must respond to.

This report will limit itself to only one of the many different activities that come under the general heading of ATC Simulation. It addresses simulations with the following characteristics: (1) controllers use plan view displays and voice communications to control simulated aircraft; (2) simulator pilots respond to, and reply with standard phraseology; (3) simulated aircraft exhibit realistic flight dynamics; (4) flight plans, flight profiles, traffic flow, and procedures are appropriate to the airspace under study.

For many applications, ATC simulation provides a useful model of the "real world." Sophisticated simulation equipment permits traffic levels, aircraft dynamics, and sector geography to be matched to today's or tomorrow's systems. Still, there are always differences. ATC simulator pilots are not usually professional pilots and they may control five or more aircraft at a time; there is no analog of cockpit workload; realistic weather is difficult to include; simulation equipment and procedures often require compromises; participating controllers may have to work with unfamiliar equipment, proce- dures and airspace; and if blunders or anomalies are introduced as part of safety testing, they soon become anticipated.

METHODOLOGICAL ISSUES. Whether or not these differences are important depends on the purposes of the simulation. Even with the limitations men- tioned, simulation offers a good projection of potential changes in system capacity and controller workload. This is especially true when current operations are tested with changes in routes or procedures, and the same controllers can participate in "before and after" tests.

The evaluation of system safety places additional demands on simulation testing. Three distinct issues are raised: simulation conditions, safety criteria, and safety standards.

DISCUSSION

SIMULATIONS CONDITIONS.

In a fairly realistic simulation environment the rare events that adversely affect safety might not ever occur, even in a long study. They certainly would not happen often enough for systematic investigation. Years of testing would be needed if results had to be stated in terms of events "per million opera- tions" or "per million hours."

Several things can be done to insure the occurrence of the rare events that are necessary for thorough system testing. These include:

1. Deliberate pilot noncompliance or miscompliance.

2. Dimulation of equipment errors and/or failures.

3. The use of unusually high traffic rates to maximize pressure on the controllers.

While the introduction of rare or unusual events is essential to safety testing, their impact on system performance is complex.

Even safe systems can be expected to have problems with unusual events, occasionally serious problems. Decision making must evaluate not only the danger in an outcome, but its likelihood. This is especially important when two rare events, with independent likelihoods, are made to occur simultaneously.

SAFETY CRITERIA.

Safety criteria are system measures and observations indicative of the safety of the system being tested. Some of the usual measures are:

1. Counts of conflicts or separation violations that occur.

2. Ratings by controllers and observers of system safety (using notes, questionnaires or debriefing after each run or series of runs).

3. Various measures and indices of aircraft proximity, such as slant range miss distance and the Aircraft Proximity Index (API).

For consensus to be reached on the interpretation of simulation results, there must be agreement on the choice of safety criteria.

If the critical safety-threatening incident in parallel runway operations is the 30° blunder,* the criteria must measure the ability of the controllers using the system to provide safe resolution. This measure should be based on the resulting separation of affected aircraft.

CONFLICTS. The definition of a conflict depends, in part, on the airspace and operations. Generally, a conflict occurs when separation between two aircraft is less than 3 miles laterally and less than 1000 feet vertically in terminal airspace, or less than 5 miles and less than 1000 feet (2000 feet above 29,000 feet) en route. There are many exceptions, such as when one pilot sees the aircraft ahead and accepts visual separation, or both aircraft are established on parallel localizers.

The occurrence of conflicts is not a useful criteria in evaluating parallel operations, since conflicts are an unavoidable result of the blunder.

Two other criteria have been used in recent studies: Slant Range Miss Distance (SRMD) and the Aircraft Proximity Index API.

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* A blunder is defined as an unexpected turn by a plane, already established on the localizer and cleared to land, towards an adjacent parallel approach.

Each is computed, second-by-second, for each aircraft pair in a conflict, with a single value, the smallest for SRMD, the largest for API, assigned to the conflict.

API follows the definition of a conflict in considering that 3 nautical miles (nmi) (18,228 feet) of horizontal distance and the 1000-foot vertical distance each provide safe separation. This makes 1 foot of vertical distance equivalent to 18 feet of lateral separation.

A comparison of the three measures is shown in figure 1. The standard definition of a conflict can be visualized as a flat cylinder surrounding an aircraft, extending 1000 feet above and below, and 3 miles in radius. SRMD treats separation as a sphere around an aircraft, with the same dimension in all directions. API can be thought of as a concentric set of discus-shaped layers surrounding an aircraft (a/c), circular in shape and tapering in thickness from the center to the edge. Figure 2 contains a set of cross sections of API values drawn to scale. Figure 3 is a set of 3-dimensional plots for APIs of 1, 25, 50 and 75. In both illustrations, one aircraft can be considered the target at the center, while the location of the intruder determines the API. The values are symmetrical around either aircraft.

<u>SRMD</u>. When a conflict occurs -- usually by the introduction of a blunder -- the slant range distance of the a/c pair is computed each second. The least distance between the centers of gravity of the two aircraft defines the SRMD. SRMD can be thought of as the radius of the smallest observed sphere, centered on one of the aircraft, the surface of which passes through the center of gravity of the other aircraft.

<u>API</u>. A detailed discussion of API is contained in the appendix. This index was developed by the author and has been reported and used in several Technical Center simulations (reference 1, 2, 3, and 4).

Computation is as follows:

D_V = vertical distance between a/c in feet

D_H = horizontal distance in nmi (6,076')

API = (1,000-DV)2*(3-DH)2/(90,000)

While it may not be obvious from the formula, API can also be expressed as the product of squared proportions of LOST standard separation, normalized from 0 to 100:

$$API = \left(1 - \frac{D_V}{1000}\right)^2 * \left(1 - \frac{D_H}{3}\right)^2 * 100$$

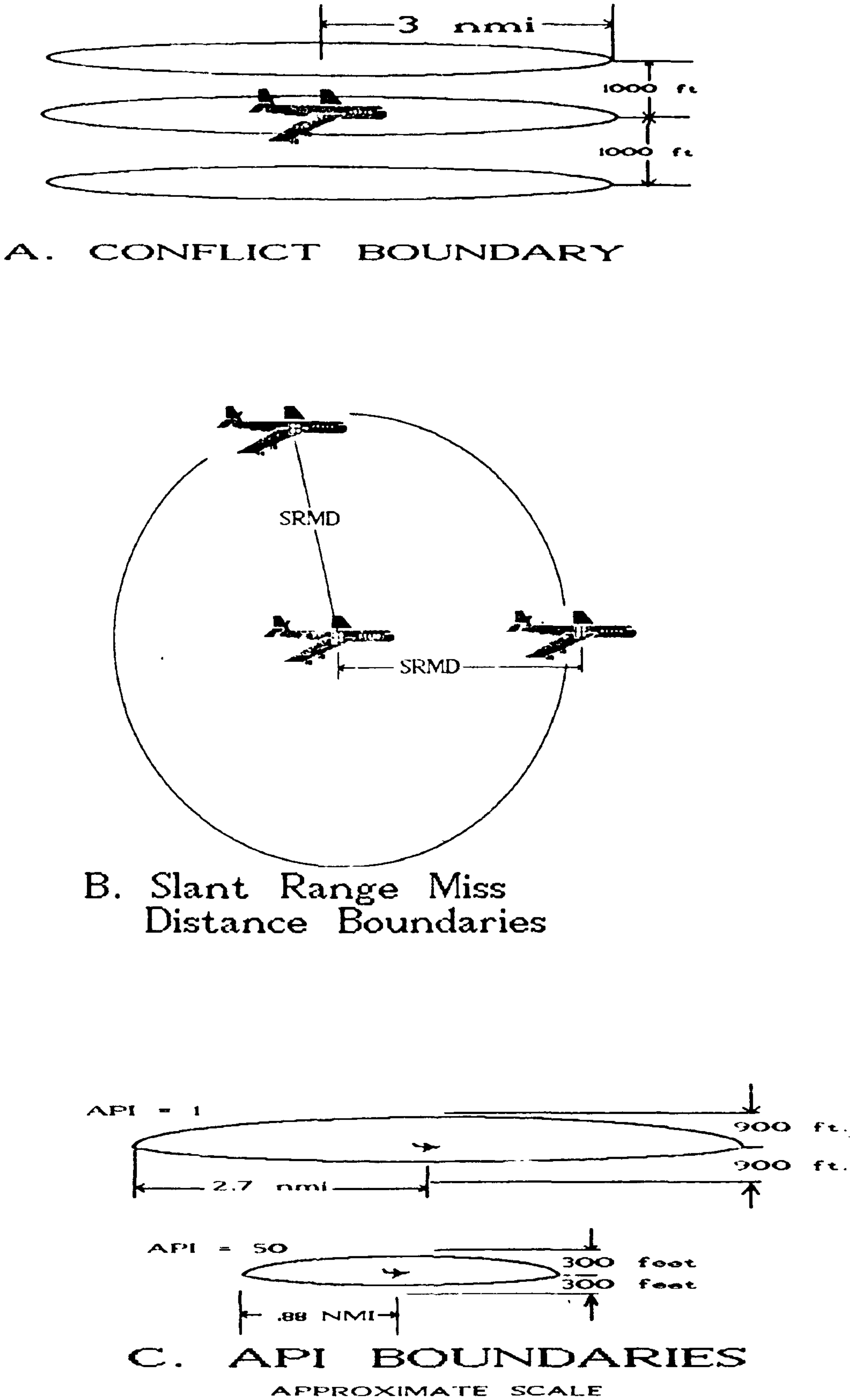

FIGURE 1. COMPARISON OF THREE SAFETY CRITERIA.

AIRCRAFT PROXIMITY INDEX (API)

TO APPROXIMATE SCALE

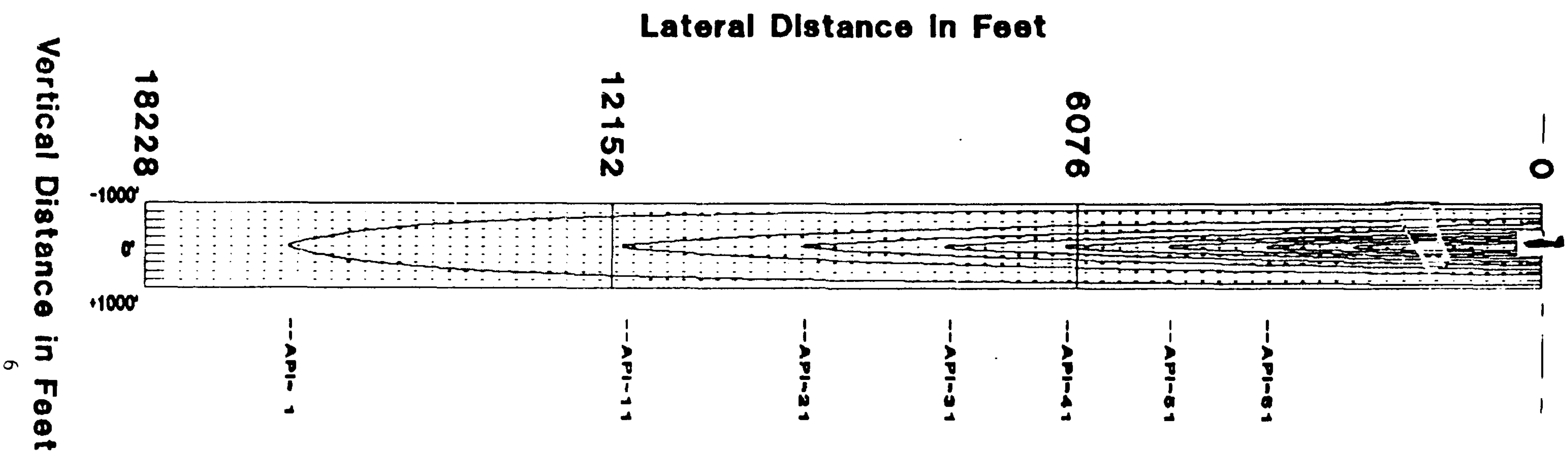

FIGURE 2. CROSS SECTIONAL VIEW OF API VALUES.

Figure 2. The boundaries of API, as seen in cross section. This is a scaled plot of API, showing a target a/c in the center at the right side. The outer rectangle defines half the conflict cylinder, plus and minus 1000 feet, and 3 nm in radius. The API surfaces for values of 1, 11, 21, etc., are described by the labeled curves (the discus, in profile.)

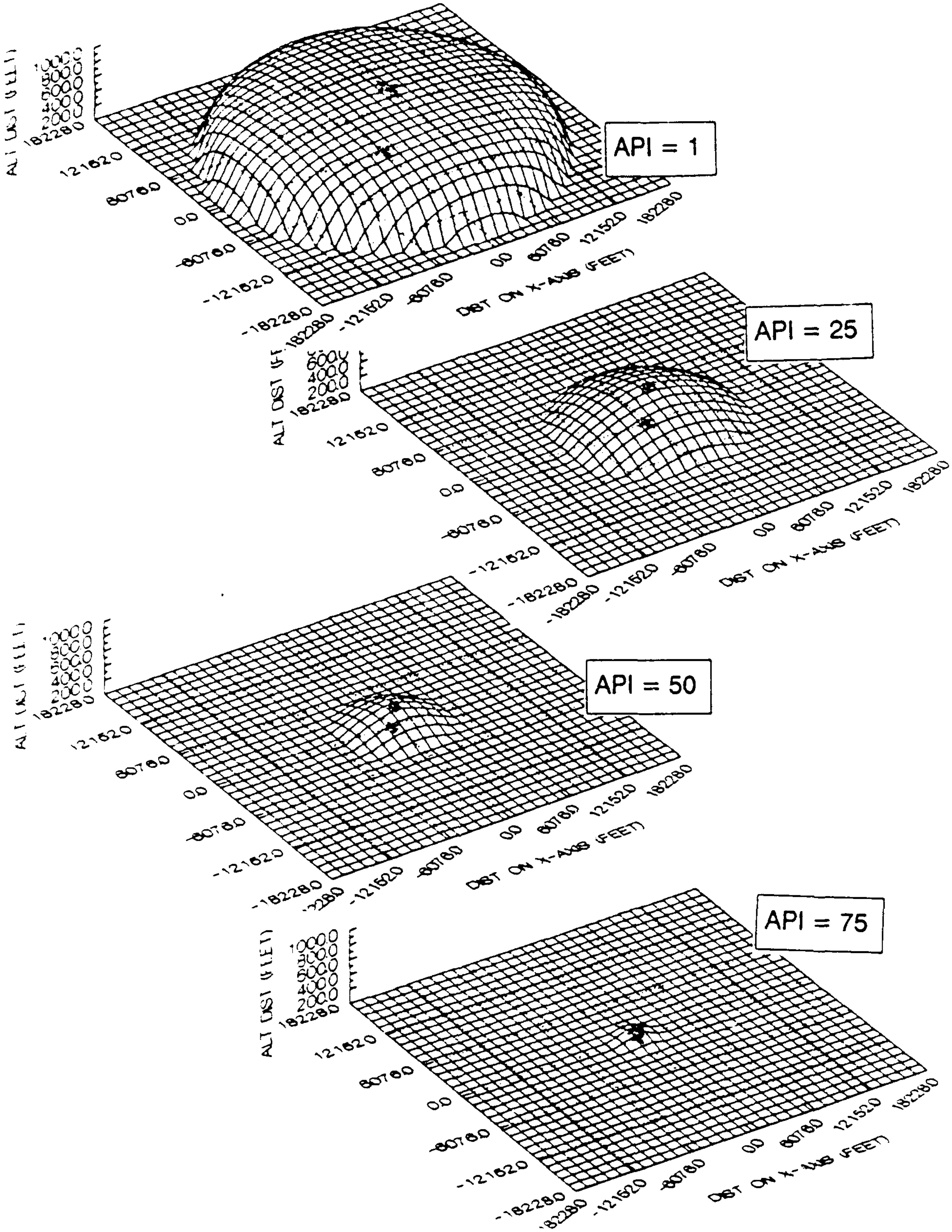

FIGURE 3. 3-DIMENSIONAL BOUNDARIES FOR FOUR VALUES OF API.

Figure 3. 3-D views of the boundaries of four values of API. as seen in cross section. The vertical scale of these plots is enlarged for clarity. The target a/c is centered on the base. The raised surface shows all possible locations of another a/c such that the API will equal the designated value. Labels around the base are in 1 nmi increments.

An example is a 60 percent loss of horizontal and vertical separation:

$$API = \left(1- \frac{400}{1000}\right)^2 * \left(1- \frac{1.2}{3}\right)^2 * 100 \quad OR \quad .6^2 * .6^2 * 100 = 12.96$$

API differs from SRMD is several respects:

1. The maximum API, 100, occurs when the centers of gravity of two aircraft are collocated. API is considered to be 0 and not calculated for horizontal separations more than 3 nmi OR vertical separations of 1000 feet or more. The highest calculated value becomes the measure of the conflict. Representative API values are shown in table A-4 in the appendix.

2. API is not linear with respect to distance. A linear decrease in distance between the aircraft, either vertically or laterally, increases the API exponentially.

3. API treats the horizontal distance between the aircraft and the vertical separation independently.

An SRMD of 500 feet can generate an API ranging from 95 (0 feet vertical, 500 feet horizontal distance) to 25 (500 vertical, 0 horizontal distance) (see figure A-4 in the appendix.)

As an example, an SRMD of 500 feet could be produced by two aircraft that miss each other by 500 feet on intersecting courses at the same altitude. If the aircraft were flying at 170 knots, or almost 287 feet per second, they would pass through the intersection less than 2 seconds apart. The API would be 95.

Another 500-foot SRMD example involves path intersection with only vertical separation. With one aircraft flying the glide slope at 170 knots (15 feet per second descent rate), the other flying level 500 feet below, it would take more than 30 seconds for them to be at the same altitude. The API would be 25.

STANDARDS.

Standards are required for reaching decisions concerning the real world that are based on the criteria. A standard should be a set of rules or procedures, agreed upon before the simulation starts, that determine how the data collected lead to proper conclusions.

One possible standard might be, "A system is not safe if any simulated event produces a clearly unsafe outcome." Another possibility is, "If a class of events that can be expected to occur no more than once every 5 years in the real world leads to an unacceptable outcome in the simulation no more than one time in 100, the system can be considered safe."

The alternatives demonstrate some of the difficulties in providing indisputable evidence of system safety. Every decision on conditions, criteria, and standards is capable of affecting results. Also, there are elements of subjectivity and judgment in designing a simulation as there are in creating and evaluating deterministic or probabilistic models.

An article by Poritzky and Horowitz (reference 5) addressed several issues relevant to the question of standards. They point out that while "Elaborate models have been constructed...neither the industry nor the FAA have found a way to validate [them] because they are derived from abstract representations with multiple assumptions about the dependence or independence of the elements, and only shaky knowledge of coprobabilities.

As a result, the application of failure probability estimating models should be viewed with skepticism for any problem other than comparing alternatives in relative terms."

With respect to safety standards, they say, "There are two separate problems: (1) problems associated with establishing the numerical value for a safety standard, and (2) problems associated with demonstrating compliance with the standard that has been established. The latter problem may...be insurmount- able."

But, under the heading "Establishing an 'Objective' Standard of Safety," they state, "On the face of it, the establishment of a standard should not be difficult. The number should be no lower than the present risk of an aircraft accident as evidenced by available statistics" (emphasis added).

While the safest standards are preferred, there is usually some trade-off between safety standards, system capacity, and system costs. These trade-offs don't lend themselves to simple analytical solutions.

<u>IMPROVING CAPACITY WHILE MAINTAINING SAFETY</u>. Capacity changes can be evaluated with real-time simulation, fast-time models, or analytically. Simulation is important if the proposed improvement may affect the controllers' job. In the case of multiple parallel runways, each runway monitor performs the same basic task, regardless of the number of run ways or monitors involved. Other things being equal (which is unlikely), airport capacity should increase with additional independent instrument runways.

Demonstrating the maintenance of safety, however, requires simulation -- unless there is a proven fast-time simulation or analysis of unquestioned validity that is applicable to the changes being proposed.

What is needed is an objective criterion that can be used to evaluate system safety. While absolute standards for system safety are exceedingly difficult to establish, a pragmatic standard can serve. The one proposed here is based on the premise: SYSTEM CHANGES SHOULD NEVER REDUCE SAFETY. That is, today's operation -- if considered safe -- can be a standard against which to test proposed changes. In experimental terms, the present operation, whether it is the number of parallel runways or the distance between them, is run as the "control," while the system to be tested, either multiple runways or closer spacing, is the "experimental condition."

All pertinent operational conditions must be included in the simulation. In the study of parallel approaches this includes an appropriate mix and number of aircraft, realistic flight technical error, appropriate radar characteristics and air/ ground communications, and the occurrence of incidents or equipment failures the system should be able to manage safely.

The same controllers run the same traffic at the same consoles and with comparable system errors introduced under both conditions. The decision standard asks whether the experimental condition is as safe as the control condition.

If enough runs are made with enough controllers and traffic, if the tests are carefully controlled to avoid extraneous factors, and if the measures of safety are relevant (valid), it will be possible to reach a conclusion on the safety of proposed system. It may be:

1. The experimental condition is not as safe as the control, or

2. The experimental condition is as safe as the control, or

3. The data are insufficient to answer the question with the necessary precision.

The ability to generalize from the simulation to the real world is possible because the proposed and present systems are evaluated under identical conditions, criteria, and standards. Only if there is some artifact in the simulation that differ- entiallv affects the two systems is a "wrong answer" likely.

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* The consoles might be different if changes in displays were part of the new system under consideration.

IMPROVING SAFETY WHILE MAINTAINING CAPACITY. The approach outlined above can be applied to the improvement of safety as well as its maintenance. Using a similar experi- mental design, only the hypothesis being tested changes. The questions to be answered might be phrased as follows:

1. The experimental condition is safer than the control.

2. The experimental condition is not safer than the control.

3. The data are insufficient to answer the question with the necessary precision.

The safety standard proposed here can be applied whether SRMD, API, or both are used as criteria. The standard requires con- ducting simulation runs using the control (the present day operations) and the experimental (proposed system) conditions while introducing large numbers of system errors or blunders.

The controllers always attempt to provide the safest separation they can in each case, and their effectiveness is measured by the SRMDs or the APIs generated by the ensuing maneuvers. Since the same controllers work under all conditions, any statistically significant differences in SRMD or API must be attributed inherent safety differences between the conditions.

It has been pointed out, that one does not normally PROVE the "null hypothesis," i.e., that there are no differences between experimental conditions. To be confident that the experimental condition is not less safe than the standard, there must be some assurance that the simulation was adequate to detect a difference if, in fact, it existed. Success here depends on the care used in planning and executing the study. But it can be confirmed if significant differences are found among variables of known importance. For parallel runway studies, these include factors such as the blunder angle, initial aircraft separations, and the presence or absence of communications.

SUMMARY

The standard described above frees experimenters and decision makers from the time-consuming, expensive, and ultimately futile pursuit of complete realism in simulation. It is still necessary to know which conditions can effect the outcome and assure they are included at appropriate levels.

The fact that some rare events result in dangerous outcomes will not be as important as the differences in outcomes between conditions. This is especially true as long as the system errors or blunders are truly rare events.

On the other hand, if actual system errors were frequent and their outcomes generally dangerous, a "safe standard" would be difficult to find.

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APPENDIX A

AN AIRCRAFT PROXIMITY INDEX (API)

AN AIRCRAFT PROXIMITY INDEX (API)

BACKGROUND.

Air Traffic Control (ATC) Simulation is an essential research tool for the improvement of the National Airspace System (NAS). Simulation can never offer all of the complexity and subtlety of the real world, with live radar, actual aircraft, full communications systems and the rest of the ATC environment, but it can provide an intensive exercise of key portions of the system -- with controllers in the loop.

Proper use of simulation starts with carefully defining the questions to be answered and then developing a simulation environment which includes the features that could influence the process under study. The selection of a simulation environment, the development of scenarios, the choice of data to be recorded, and the method of analysis are part science, part art.

An important benefit of simulation is that it permits the exploration of systems, equipment failures, and human errors that would be too dangerous to study with aircraft, or that occur so rarely in the system that they cannot be fully understood and evaluated. A current example of this use has to do with the introduction of blunders[1] in parallel runway instrument approaches.

The introduction of large numbers of system errors is a useful way to study safety, but the analysis of the outcomes of these incidents is not always simple or clear cut.

SAFETY EVALUATION.

1. Conflicts.

The occurrence of a conflict in normal ATC operations is considered prima facie evidence of a human or system error. Identifying (and counting) conflicts under a variety of conditions is one way to expose a system problem.

> A conflict is defined as the absence of safe separation between two aircraft flying under Instrument Flight Rules (IFR). At its simplest, safe separation requires: (a) the aircraft must be laterally separated by 3 or 5 nmi, depending on distance from the radar, (b) vertical separation by 1,000 or 2,000 feet, depending on altitude or flight level, or (c) that both aircraft are established on ILS localizers.
>
> There are refinements of the above rules that take into consideration the fact that one aircraft may be crossing behind another, or that an aircraft has begun to climb or descend from a previous altitude clearance. There are also special "wakes and vortices" restrictions for aircraft in trail behind heavy aircraft.

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[1]A blunder is defined as an unexpected turn towards an adjacent approach by an aircraft already established on the Instrument Landing System (ILS).

Since actual conflicts are rare, every event leading up to them and all the information available on the onset and resolution is carefully analyzed. The emphasis is on the intensive investigation of the particular event.

In scientific investigation, the intensive study of a single individual or a particular event is called the **idiographic** approach. This is often contrasted with the **nomothetic** approach: the study of a phenomenon or class of events by looking at large numbers of examples and attempting to draw general conclusions through the application of statistics.

The idiographic approach is mandatory for accident or incident investigation where the goal is to get as much information as possible about a unique event in order to prevent future occurrences.

In a simulation experiment, where the goal is to make a comparison between two or more systems (2 vs 3 or 4 runways, 4300 vs 3000-foot runway spacing, etc.) and to generalize beyond the simulation environment, the nomothetic approach is most appropriate. This means generating a large numbers of events and statistically analyzing the outcomes with respect to the system differences.

There is much to be gained by studying the individual conflicts in a simulation as an aid to understanding the kinds of problems that occur and to generate hypotheses about how a system might be improved for subsequent testing. But the evaluation of the systems under test requires the use of all of the valid data, analyzed in as objective a manner as possible. Valid data in this context means that it was collected under the plan and rules of the simulation and was not an artifact, such as a malfunction of the simulation computer or distraction by visitors.

2. Slant Range.

If it is important to go beyond the counting of conflicts, measurement of the distance between the conflicting aircraft pair is required. The most obvious measure is slant range separation: the length of an imaginary line stretched between the centers of each aircraft. Over the course of the incident that distance will vary, but the shortest distance observed is one indication of the seriousness or danger of the conflict.

The problem with slant range is that it ignores the basic definition of a conflict and is insensitive to the different standards that are set for horizontal and vertical separation. A slant range distance of 1100 feet might refer to 1000 feet of vertical separation, which is normally perfectly safe, to less than 0.2 nmi of horizontal miss distance, which would be considered by most people to be a very serious conflict. Slant range, per se, is too ambiguous a metric to have any real analytical value.

3. API.

The need exists for a single value that reflects the relative seriousness or danger. The emphasis here is on "relative," since with the nomothetic or statistical approach, an absolute judgment of dangerous or safe is useful, but not sensitive enough. The requirement is to look at the patterns of the data for the different experimental conditions and determine whether one pattern indicates more, less, or the same degree of safety as another.

Such an index should have to have certain properties.

a. It should consider horizontal and vertical distances separately, since the ATC system gives 18 times the importance to vertical separation (1,000 ft vs 3 nmi).

b. It should increase in value as danger increases, and go to zero when there is no risk, since the danger in the safe system is essentially indeterminate.

c. It should have a maximum value for the worst case (collision), so that users of the index can grasp its significance without tables or additional calculations.

d. It should make the horizontal and vertical risk or danger independent factors, so that if either is zero, i.e., safe, their product will be zero.

e. It should be a nonlinear function, giving additional weight to serious violations, since they are of more concern than a number of minor in fractions.

The API is designed to meet these criteria. It assigns a weight or value to each conflict, depending on vertical and lateral separation. API facilitates the identification of the more serious (potentially dangerous) conflictions in a data base where many conflictions are present. One hundred has been chosen, somewhat arbitrarily, for the maximum value of the API.

APPROACH.

During a simulation API can be computed whenever a conflict exists. For convenience, this is taken to be when two aircraft have less than 1,000 feet of vertical separation AND less than 3.0 nmi of lateral separation. It is computed once per second during the conflict. The API of the conflict is the largest value obtained.

API considers vertical and horizontal distances separately, then combines the two in a manner than gives them equal weight; equal in the sense that a loss of half the required 3.0 nmi horizontal separation has the same effect as the loss of half the required 1000 feet of vertical separation.

COMPUTATION.

The API ranges from 100 for a mid-air collision to 0 for the virtual absence of a technical confliction. A linear decrease in distance between the aircraft, either vertically or laterally, increases the API by the power of 2.

Computation is as follows:

D_V - vertical distance between a/c (in feet)

D_H - horizontal distance (nmi (6,076'))

API - $(1{,}000-D_V)^2*(3-D_H)^2/(90{,}000)$

To simplify its use, API is rounded off to the nearest integer, i.e.,

$$API = INT((1,000-D_V)^2*(3-D_H)^2/(90,000)+.5)$$

The rounding process zeros API's less than 0.5. This includes distances closer than 2 nmi AND 800 feet. The contour plot in figure A-1, demonstrates the cutoff for API = 1.

See tables A-1 and A-2 for typical values of API at a variety of distances.

Figure A-2 is a three-dimensional plot showing the relationship between API and vertical and horizontal separation graphically. Figure A-3 shows the same information in a slightly different way. Anything outside the contour at the base is "0". In figure A-4 a contour plot of API for horizontal and vertical distances from 0 to 500 feet is shown, with 300-foot and 500-foot slant range distances superimposed.

DISCUSSION.

The index is not intended as a measure of acceptable risk, but it meets the need to look at aircraft safety in a more comprehensive way than simply counting conflictions or counting the number of aircraft that came closer than 200 feet, or some other arbitrary value.

It should be used to compare conflicts in similar environments, i.e., an API of 70 in en route airspace with speeds of 600 knots is not necessarily the same concern as a 70 in highly structured terminal airspace with speeds under 250 knots.

Since the API is computed every second, it may be useful to examine its dynamics over time as a means of understanding the control process.

TABLE 1. TYPICAL VALUES

VERTICAL DISTANCE (D_V) (in feet)	HORIZONTAL DISTANCE IN NAUTICAL MILES (1 NM = 6076')(D_H) 3	2.5	2.0	1.5	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1	.05	.01	-0-
1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
900	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
800	0	0	0	1	2	2	2	2	3	3	3	3	3	4	4	4	4
700	0	0	1	2	4	4	5	5	6	6	7	7	8	8	9	9	9
600	0	0	2	4	7	8	9	9	10	11	12	13	14	15	15	16	16
500	0	1	3	6	11	12	13	15	16	17	19	20	22	23	24	25	25
400	0	1	4	9	16	18	19	21	23	25	27	29	31	34	35	36	36
300	0	1	5	12	22	24	26	29	31	34	37	40	43	46	47	49	49
200	0	2	7	16	28	31	34	38	41	44	48	52	56	60	62	64	64
100	0	2	9	20	36	40	44	48	52	56	61	66	71	76	78	80	81
-0-	0	3	11	25	44	49	54	59	64	69	75	81	87	93	97	99	100

TABLE 2. ADDITIONAL VALUES

D_H	D_V	API	D_H	D_V	API	D_H	D_V	API
3.0	1000	0	1.0	667	5	.05	667	11
3.0	0	0	1.0	500	11	.05	500	24
0	1000	0	1.0	333	20	.05	333	43
2.0	667	1	1.0	250	25	.05	250	54
2.0	500	3	1.0	100	36	.05	100	78
2.0	333	5	1.0	0	44	.05	0	97
2.0	250	6	.5	667	8	.01	667	11
2.0	100	9	.5	500	17	.01	500	25
2.0	0	11	.5	250	39	.01	333	44
1.5	667	3	.5	100	56	.01	250	56
1.5	500	6	.5	0	69	.01	100	80
1.5	333	11	.1	667	10	.01	0	99
1.5	250	14	.1	500	23	0	667	11
1.5	100	20	.1	250	53	0	500	25
1.5	0	25	.1	100	76	0	333	44
			.1	0	93	0	250	56
						0	100	81
						0	0	100

A/C PROXIMITY INDEX (API)

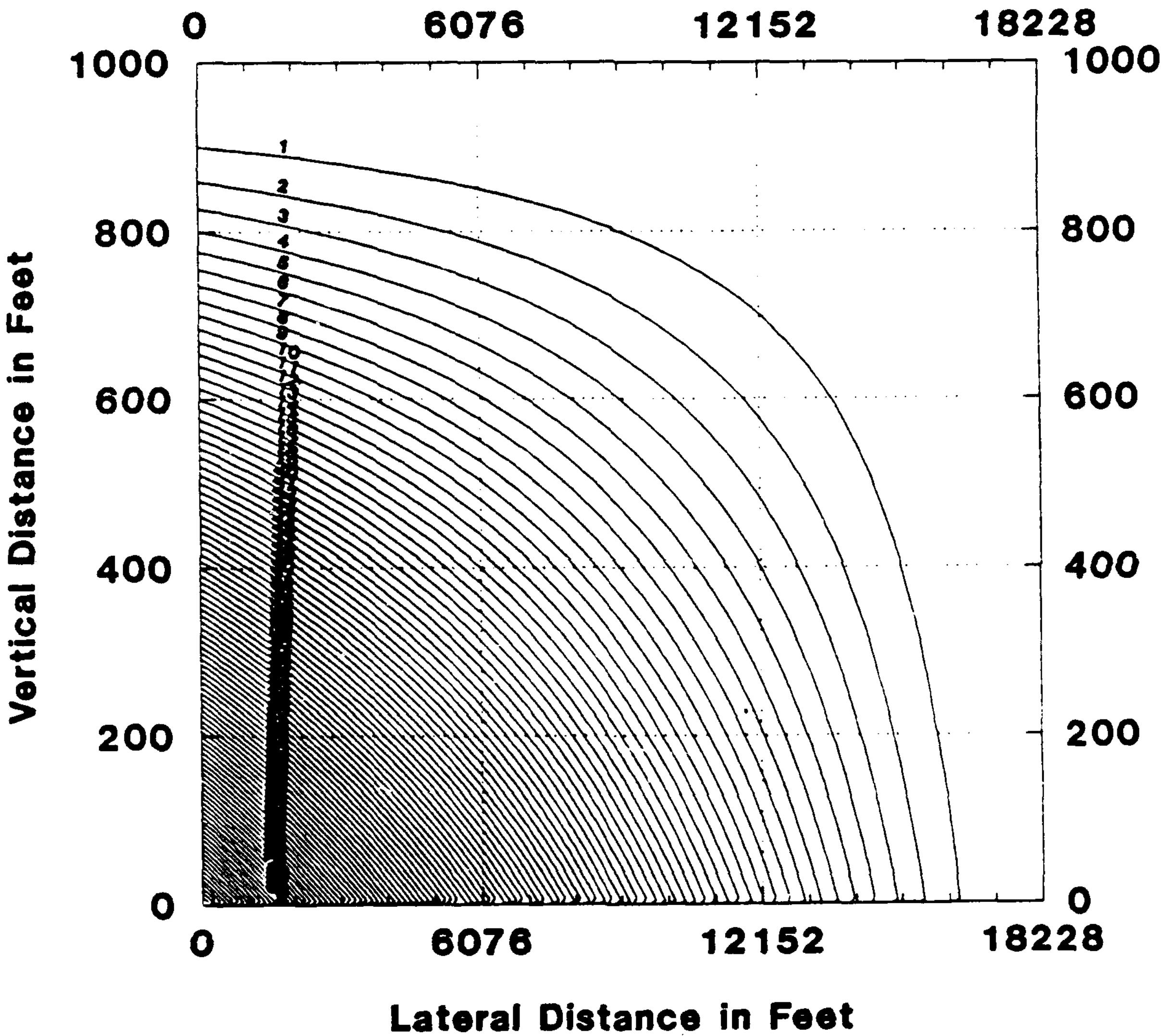

FIGURE 1. CONTOUR PLOT

This is a contour plot of API. showing the values of API for the horizontal separations of 0 to 3 nmi, and vertical separation of 0 to 1,000 feet. Values less than API = .5 round to zero. This includes a/c separated by as little 1.6 nmi horizontally AND 850 feet vertically.

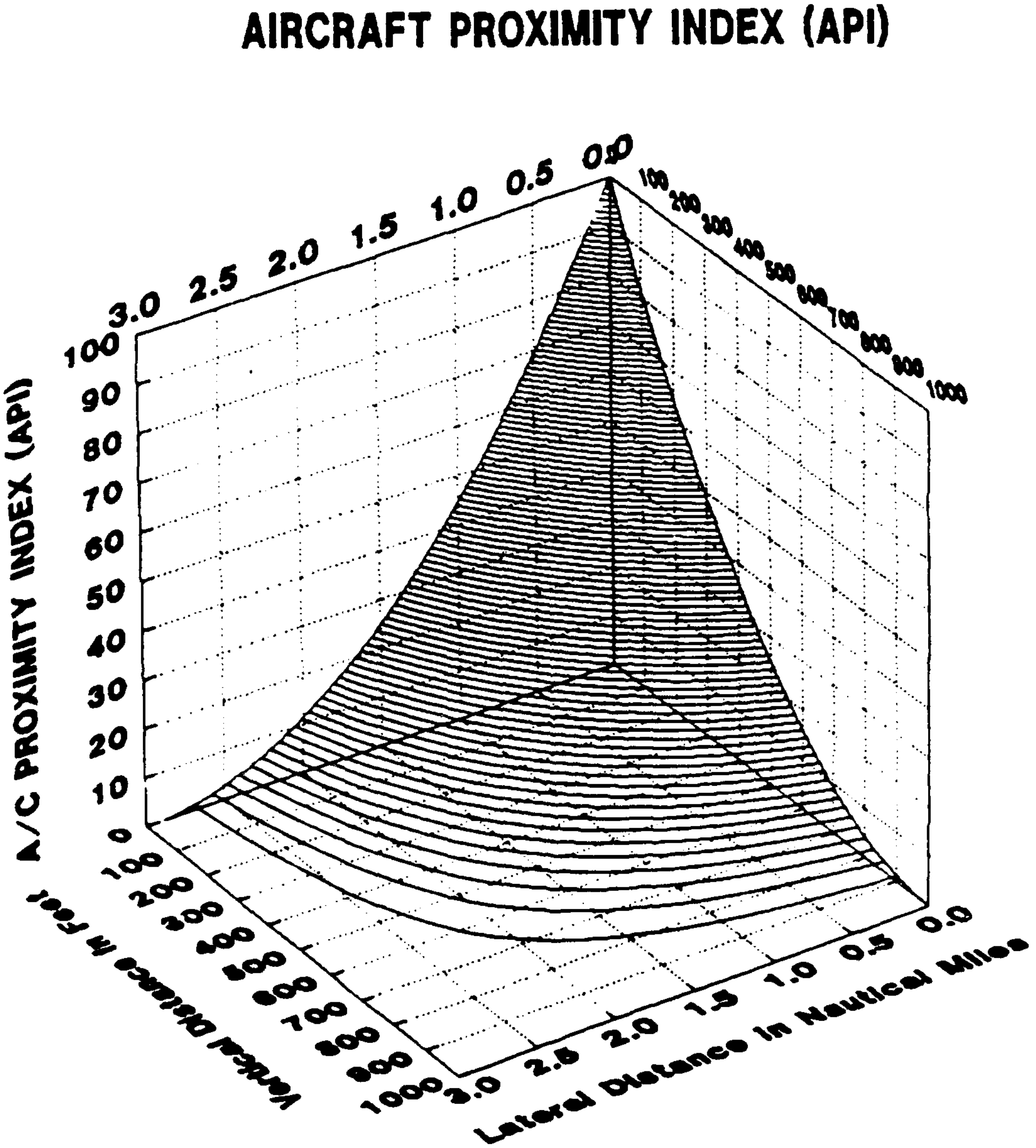

FIGURE 2. 3-DIMENSIONAL CONTOUR PLOT

Three-dimensional contour plot of API, for horizontal separations of 0 to 3 nmi, and vertical separations of 0 to 1,000 feet.

AIRCRAFT PROXIMITY INDEX (API)

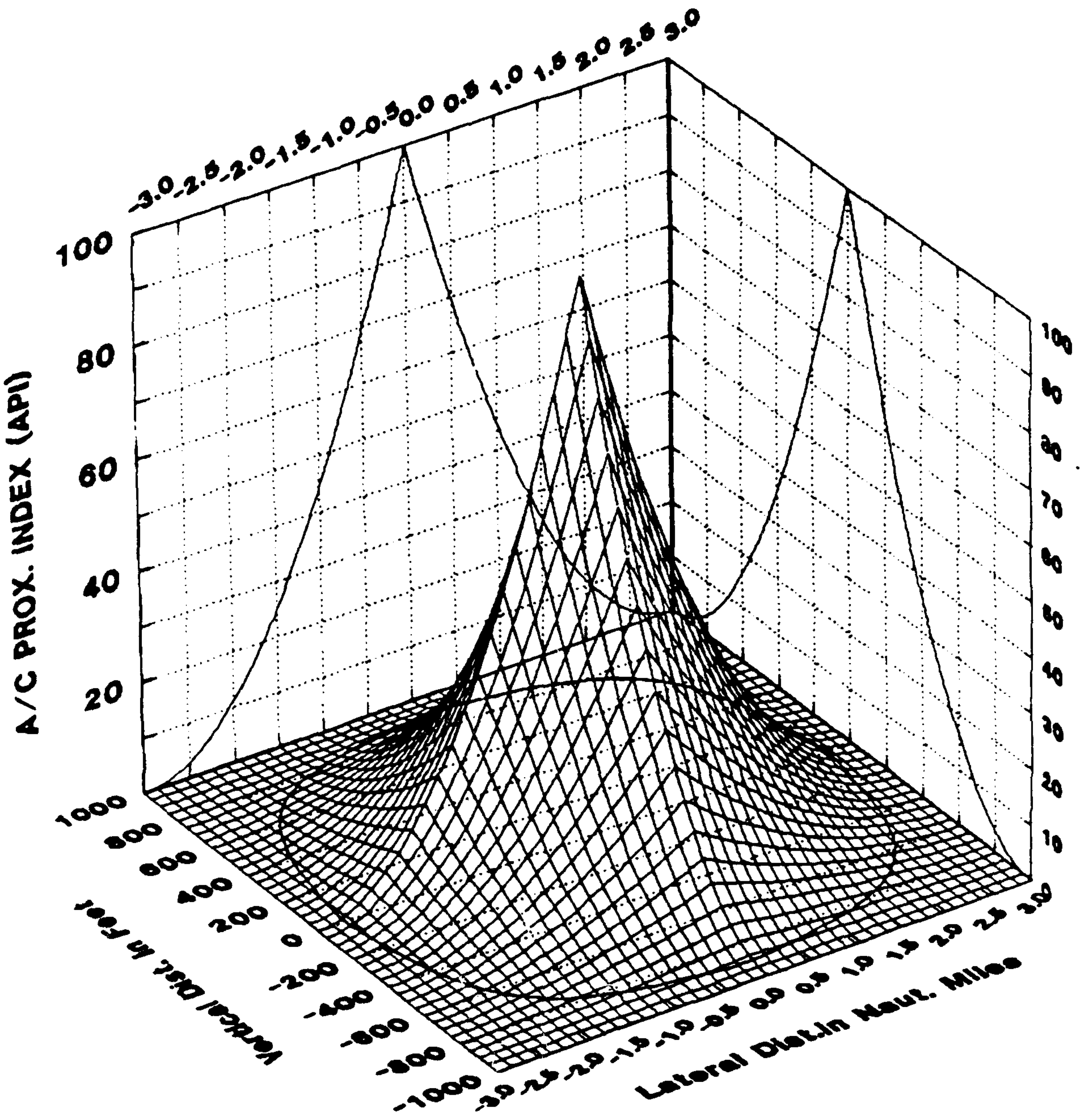

FIGURE 3. 3-DIMENSIONAL CONTOUR PLOT

Left vertical plane shows API vs horizontal distance with vertical distance=0. Right vertical plane shows API vs vertical separation with horizontal distance = 0.

Plot may be interpreted by considering one a/c at the center of the base plane, while the height of the figure shows the API for another a/c anywhere else on the base plane.

The contour on the base plane shows the boundary between API =0 and API=1.

A/C PROXIMITY INDEX (API)

API VALUES FOR SLANT RANGES OF 300 AND 500 FEET

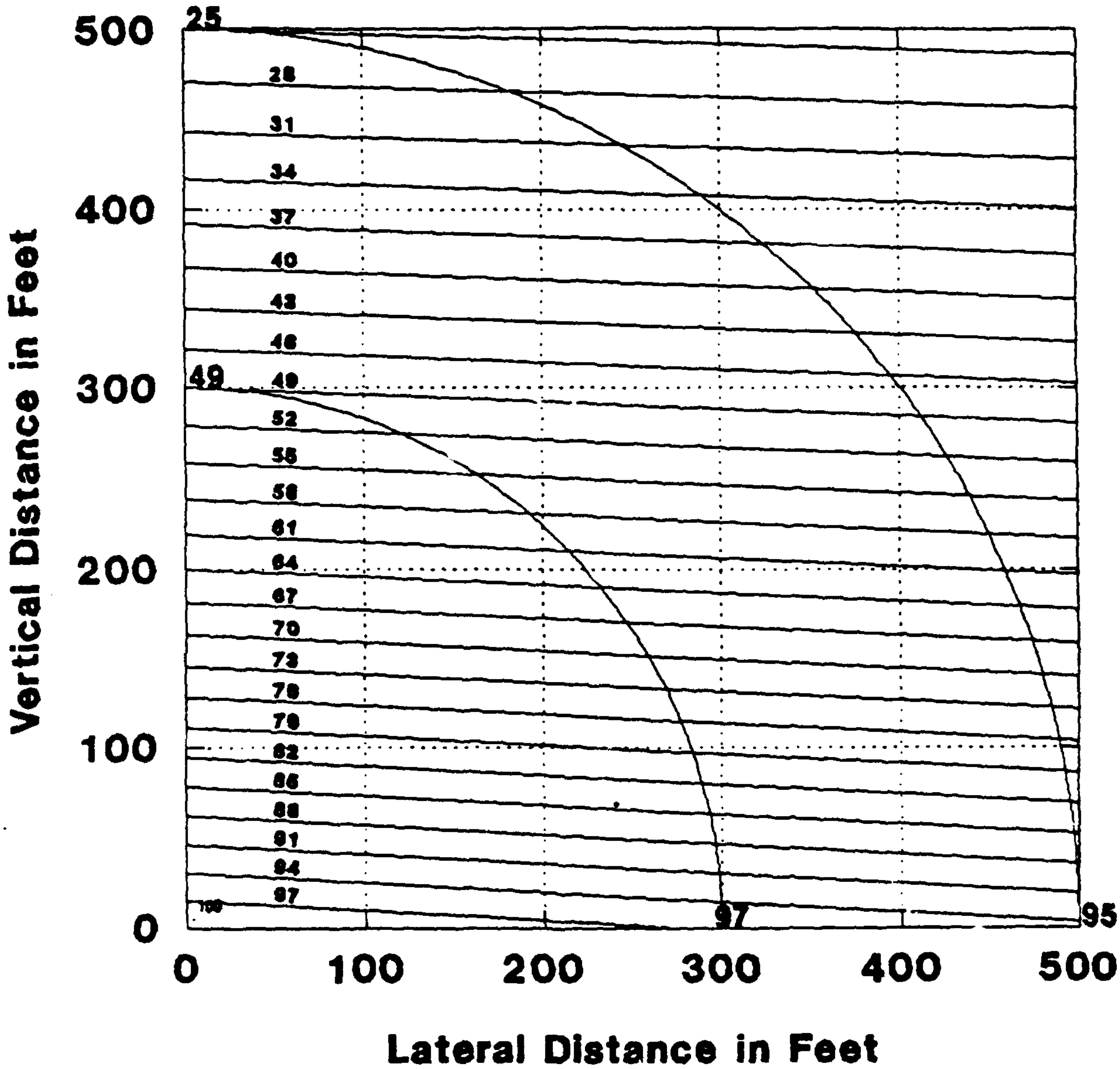

FIGURE 4. CONTOUR PLOT OF API FOR HORIZONTAL AND VERTICAL DISTANCES OF 0 TO 500 FEET, SHOWING SLANT RANGE CONTOURS OF 300 AND 500 FEET

This plot shows the API values (the small numbers, inside the square running from 25 at the top to 100 at the bottom) for equal API contours (the slightly sloping horizontal lines) for horizontal and vertical distances of 0 to 500 feet. API values range from 25 (500-foot vertical, 0 horizontal separation) to 100 (0/0).

The 500-foot slant range contour has API values ranging from 25 to 95, depending on amount of vertical component. The 300-foot slant range contour runs from API = 49 to 97. Using API as a criterion, 500-foot slant range can be more dangerous than 300-foot.